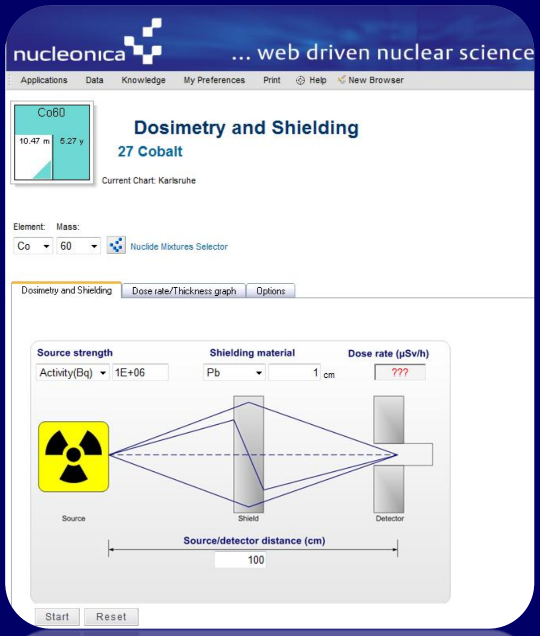
# Shielding of Ionising Radiation
## with the Dosimetry & Shielding Module

J. Magill




## Overview…

### Biological Effects of Ionising Radiation

- Absorber dose, Quality or Weighting Factor, Equivalent Dose

### Attenuation of Gamma Radiation

- Calculation of the energy absorption, calculation of the equivalent dose rate, absorption in tissue, attenuation in shield materials, build-up factors

### Nucleonica´s Dosimetry & Shielding Module

## Absorbed Dose

Usually the interaction of radiation with matter involves a transfer of energy from the radiation to the matter. Ultimately, the energy transferred either to tissue or to a radiation shield is dissipated as heat. The radiation dose depends on the intensity and energy of the radiation, the exposure time, the area exposed and the depth of energy deposition.

The modern SI unit of absorbed dose is the gray (Gy) where one gray is one joule per kilogram 1Gy = 1 J $kg^{-1}$. In dosimetry, it is useful to define an average dose for a tissue or organ $D_T$. The absorbed dose to the mass $\delta m_T$, is defined as the imparted energy $\delta E_T$ per unit mass of the tissue or organ, i.e.

$$D_T = \delta E_T / \delta m_T.$$

The absorbed dose rate is the rate at which an absorbed dose is received. The units are Gy $s^{-1}$, mGy $hr^{-1}$, etc.

Biological effects depend not only on the total dose to the tissue but also on the rate at which this dose was received. In organisms, mechanisms exist which enable molecules such as deoxyribonucleic acid (DNA) to recover if they have not been too badly damaged. Hence it is possible for organs to recover from a potentially lethal dose provided that the dose was supplied at a sufficiently slow rate. This phenomena is exploited in cancer radiotherapy

**Quality or Weighting Factor**

The biological effect of radiation is not just directly proportional to the energy deposited by radiation in an organism. It depends, in addition, on the way in which the energy is deposited along the path of the radiation, and this in turn depends on the type of radiation and its energy.

Thus for the same absorbed dose, the biological effect from high LET radiation such as α particles or neutrons is much greater than that from low LET radiation such as β or γ rays.

The quality or weighting factor, $w_R$, is introduced to account for this difference in the biological effects of different types of radiation. The weighting factors for the various types of radiation and energies is given in the table.

Quality or weighting factors for different types of radiation

| Radiation type | Radiation weighting factor, $w_R$ |
|---|---|
| Photons | 1 |
| Electrons[a] and muons | 1 |
| Protons and charged pions | 2 |
| Alpha particles, fission fragments, heavy ions | 20 |
| Neutrons | A continuous function of neutron energy<br>See Radiation weighting factors |

All values relate to the radiation incident on the body or, for internal radiation sources, emitted from the incorporated radionuclide(s).

[a] Note the special issue of Auger electrons discussed in ICRP 103 (2007).

$$H_{T,R} = w_R \cdot D_{T,R} ,$$

*where* $H_{T,R}$ is the equivalent dose in tissue T and $w_R$ is the radiation weighting factor

The SI unit of dose is the Sievert, Sv (1 Sv = 1 J kg-1, the old unit is the rem, 1 Sv = 100 rem).
This is the equivalent dose arising from an absorbed dose of 1 Gy

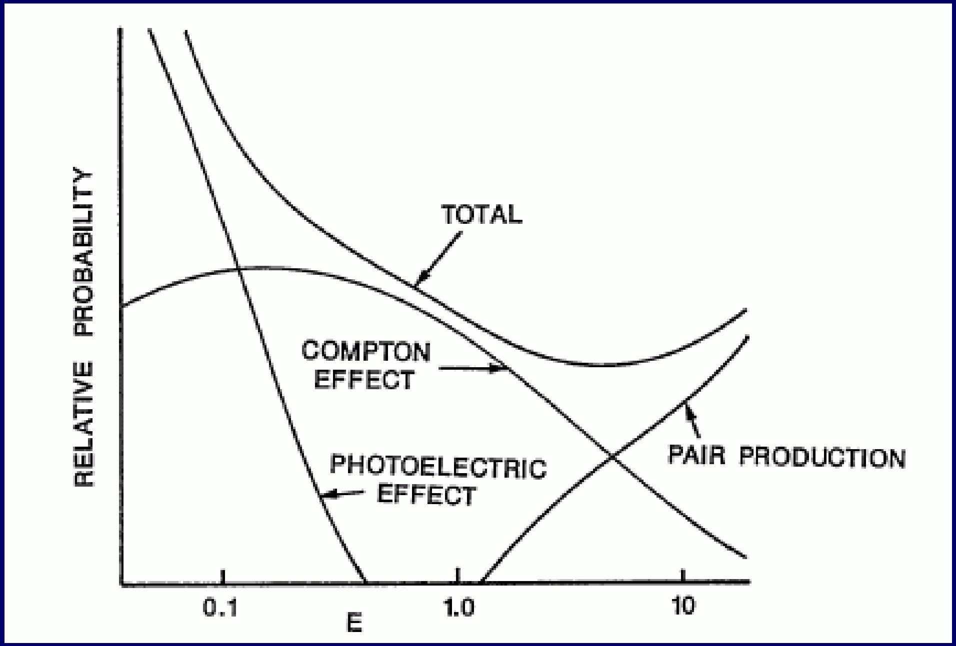
# Attenuation of Gamma Radiation

The attenuation coefficient discussed above is a measure of how photons are removed from the beam under conditions of good geometry. Attenuation is a result of three basic processes: the photoelectric effect (pe), Compton scattering (cs), and pair production (pp) and the total attenuation coefficient is a sum of the attenuation coefficients for these processes.

$$\mu = \mu_{pe} + \mu_{cs} + \mu_{pp}$$

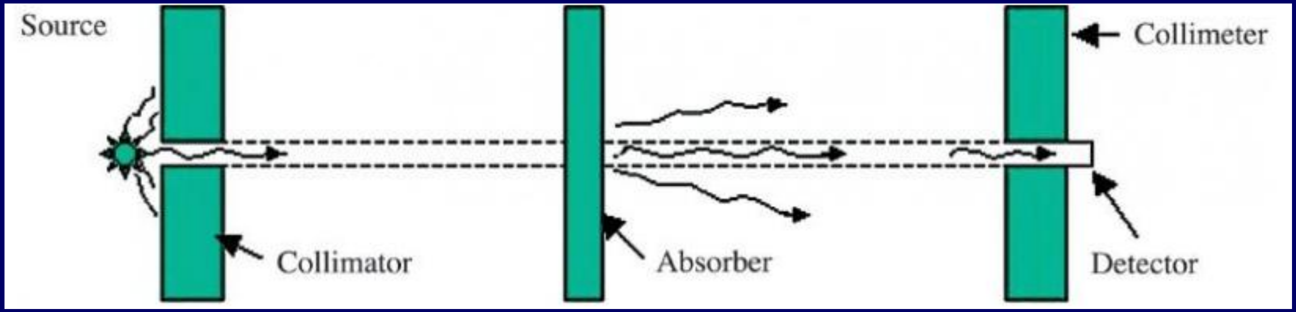
*The total attenuation coefficient μ given above is the fraction of the energy of the beam that is removed per unit distance in the medium. The energy absorbed in the medium is determined by the energy absorption coefficient $\mu_{en}$. The difference between μ and $\mu_{en}$ results from the fact that energy may be lost from the medium through Compton scattering and by annihilation radiation.*

- *For dose calculations in tissue for example, the energy absorption coefficient $\mu_{en}$ must be used.*
- *For shielding calculations, the attenuation coefficient should be used.*



# Attenuation of Gamma Radiation

Gamma radiation cannot be completely absorbed, but only reduced in intensity, when passing through matter. If mono-energetic gamma radiation attenuation measurements are made under conditions of good geometry, i.e. with a well-collimated, narrow beam of radiation, as shown in Fig. 1, a straight-line relationship between the logarithm of the intensity versus the thickness d of the shield is obtained.




$$\frac{I}{I_0} = e^{-\mu d}$$

$$I = I_0 \cdot e^{-(\mu_t/\rho)\cdot(\rho d)}$$

# Calculation of the Energy Absorption

Consider an idealised broad, parallel beam of monoenergetic photons passing through a thin layer of material. If the incident intensity energy per unit area per second) is denoted by $I_0$, the transmitted intensity is given by:

$$I = I_0 \cdot e^{-\mu x}$$

For thin layers, $\mu x << 1$ such that $e^{-\mu x} = 1 - \mu x$. Hence the above relation becomes

$$I_0 - I = I_0 \cdot \mu x$$

The rate at which energy is absorbed over an area A is $(I_0 - I) \cdot A = I_0 \cdot \mu x \cdot A$. Since the mass of the slab over the area A is $\rho \cdot A \cdot x$, where $\rho$ is the density, The rate of energy absorption per unit mass dD/dt is given by

$$dD/dt = I_0 \cdot \mu x \cdot A / (\rho \cdot A \cdot x) = I_0 \cdot \mu / \rho$$

or

$$\Rightarrow dD/dt = I_0 \cdot \mu / \rho$$

# Calculation of the Energy Absorption

The quantity dD/dt is the average dose rate in the thin layer. Under conditions of electronic equilibrium, it is also the dose rate at a point in a medium and is equal to the product of the intensity $I_0$, or energy fluence rate, at the point and the mass energy-absorption coefficient (μ/ρ). The absorption coefficent is the energy absortion coefficent $\mu_{en}$ so that the dose rtae is given by

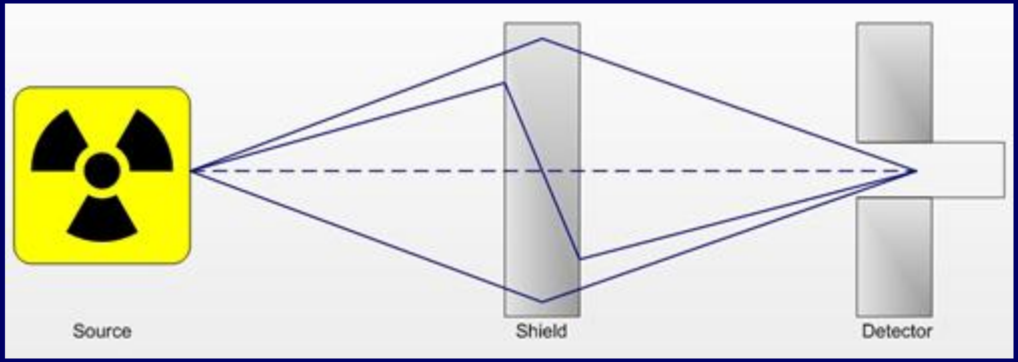
$$\text{Dose rate} = dD/dt = I_0 \cdot \mu_{en} / \rho$$

In contrast to the mass energy absortion coefficent, $\mu_{en}$, there is also the mass energy transfer coeficient, $\mu_{tr}$, which refers to the total energy transferred out of the layer. This latter quantity is called the kerma rate in the layer i.e.

$$\text{Kerma rate} = dK/dt = I_0 \cdot \mu_{tr} / \rho$$

In general the kerma is defined as the total initail kinetic energy of all charged particles liberated by uncharged radiaiton photons, neutrons) per unit mass of material.

However, under conditions of poor geometry, i.e. for a broad beam or for a very thick shield, the above relation underestimates the required shield thickness. It assumes that every photon that interacts with the shield will be removed from the beam and thus will not be available for counting in the detector. Under conditions of poor geometry, as shown in Figure, this assumption is not valid; a significant number of photons may be scattered by the shield into the detector, or photons that had been scattered out of the beam may be scattered back in after a second collision.




Gamma radiation attenuation under conditions of broad beam geometry showing the effect of photons scattered into the detector

The shield thickness for conditions of poor geometry may be estimated by modification of the basic attenuation relation given above through the use of a build-up factor B, i.e.

$$I = B \cdot I_0 \cdot e^{-(\mu_t/\rho)\cdot(\rho d)}$$

# Calculation of the Equivalent Dose Rate

$$\frac{dH}{dt}(Sv/h) = (5.77 \cdot 10^{-4}) \cdot A/(4\pi R^2) \cdot \sum_i E_i(keV) \cdot P_i \cdot B_i \cdot e^{-(\mu_l/\rho)_i^{shield} \cdot (\rho d)} (\mu_l/\rho)_i^{tis}$$

See course manuscript

$$\frac{dH}{dt}(Sv/h) = (5.77\cdot10^{-4})\cdot A/(4\pi R^2)\cdot\sum_i E_i(keV)\cdot P_i\cdot B_i\cdot e^{-(\mu_l/\rho)_i^{shield}\cdot(\rho d)}(\mu_l/\rho)_i^{tis}$$

## Absorption in Tissue

The dependence of $(\mu/\rho)_{tis}$ on energy is shown in Fig. 1. This data has been taken from the NIST database. In the calculations, a linear interpolation is carried out (actually the linear interpolation is carried out on the log (mass-absorption coefficient) vs. log(energy) plot). For energies lower than the minimum energy (0.001 MeV), an extrapolation is performed.

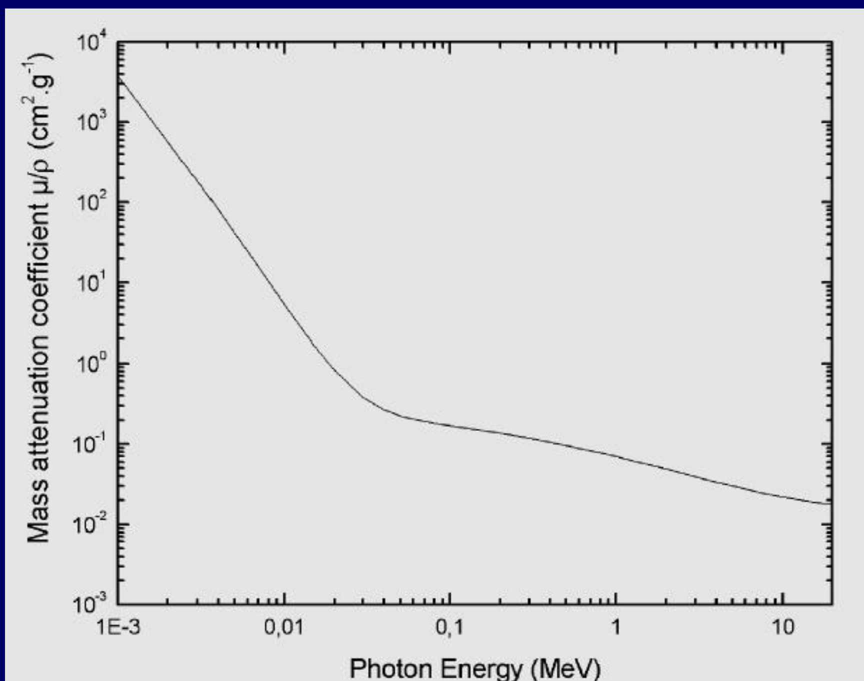



Fig.1a. Mass absorption coefficient for tissue

| Energy (MeV) | $(\mu/\rho)^{tis}$ ($cm^2\,g^{-1}$) | Energy (MeV) | $(\mu/\rho)^{tis}$ ($cm^2\,g^{-1}$) | Energy (MeV) | $(\mu/\rho)^{tis}$ ($cm^2\,g^{-1}$) |
|---|---|---|---|---|---|
| 1.00E–03 | 3.70E+03 | 8.00E–03 | 9.94E+00 | 6.00E–01 | 3.25E–02 |
| 1.04E–03 | 3.38E+03 | 1.00E–02 | 4.99E+00 | 8.00E–01 | 3.18E–02 |
| 1.07E–03 | 3.08E+03 | 1.50E–02 | 1.40E+00 | 1.00E+00 | 3.07E–02 |
| 1.50E–03 | 1.25E+03 | 2.00E–02 | 5.66E–01 | 1.25E+00 | 2.94E–02 |
| 2.00E–03 | 5.58E+02 | 3.00E–02 | 1.62E–01 | 1.50E+00 | 2.81E–02 |
| 2.15E–03 | 4.57E+02 | 4.00E–02 | 7.22E–02 | 2.00E+00 | 2.58E–02 |
| 2.30E–03 | 3.78E+02 | 5.00E–02 | 4.36E–02 | 3.00E+00 | 2.26E–02 |
| 2.47E–03 | 3.09E+02 | 6.00E–02 | 3.26E–02 | 4.00E+00 | 2.05E–02 |
| 2.64E–03 | 2.59E+02 | 8.00E–02 | 2.62E–02 | 5.00E+00 | 1.90E–02 |
| 2.82E–03 | 2.14E+02 | 1.00E–01 | 2.55E–02 | 6.00E+00 | 1.79E–02 |
| 3.00E–03 | 1.82E+02 | 1.50E–01 | 2.75E–02 | 8.00E+00 | 1.64E–02 |
| 3.61E–03 | 1.06E+02 | 2.00E–01 | 2.94E–02 | 1.00E+01 | 1.55E–02 |
| 4.00E–03 | 8.03E+01 | 3.00E–01 | 3.16E–02 | 1.50E+01 | 1.42E–02 |
| 5.00E–03 | 4.14E+01 | 4.00E–01 | 3.25E–02 | 2.00E+01 | 1.36E–02 |
| 6.00E–03 | 2.39E+01 | 5.00E–01 | 3.27E–02 | | |

Fig.1b. Table of mass absorption coefficients for tissue

$$\frac{dH}{dt}(Sv/h) = (5.77 \cdot 10^{-4}) \cdot A/(4\pi R^2) \cdot \sum_i E_i(keV) \cdot P_i \cdot B_i \cdot e^{-(\mu_t/\rho)_i^{shield} \cdot (\rho d)} (\mu_t/\rho)_i^{tis}$$

Example: Calculate the gamma dose rate from 1 MBq of $^{60}Co$. The six gamma energies and their emission probabilities are shown in Table.

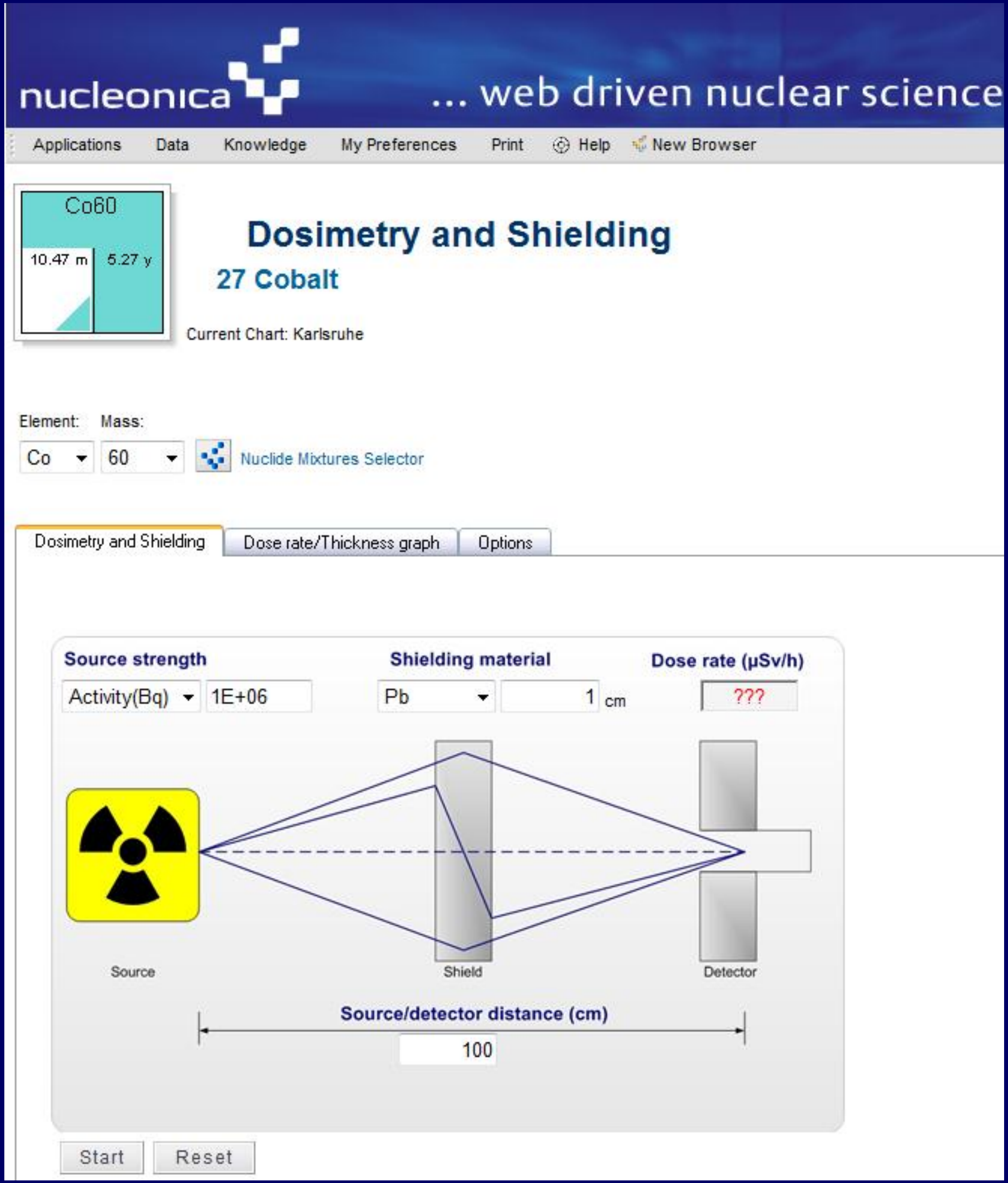
Spectral data for $^{60}Co$

| $E$ (eV) | $P$ | $\mu/\rho$ ($cm^2\ g^{-1}$) | $E$(keV) · $P$ | $E$(keV) · $P$ · $\mu/\rho$ ($cm^2\ g^{-1}$) |
|---|---|---|---|---|
| 1.3325E+06 | 9.9980E–01 | 0.0289 | 1.3322E+03 | 38.50 |
| 1.1732E+06 | 9.9900E–01 | 0.0298 | 1.1720E+03 | 34.87 |
| 8.2628E+05 | 7.6000E–05 | 0.0321 | 6.2797E–02 | 0.002016 |
| 3.4693E+05 | 7.6000E–05 | 0.0316 | 2.6367E–02 | 0.00083 |
| 2.1588E+06 | 1.1000E–05 | 0.0252 | 2.3747E–02 | 0.00060 |
| 2.5050E+06 | 2.0000E–08 | 0.0240 | 5.0100E–05 | 0.00001 |
| | | Sum = | 2.5044E+03 | 73.37 |

# Nucleonica's Dosimetry & Shielding Module

The Dosimetry and Shielding in Nucleonica allows the user to calculate gamma dose rates from point sources of single nuclides and nuclide mixtures. The user interface is shown in figure.

The main tab allows the user to select the nuclide, its source strength, source / detector distance, shield material and material thickness.



Results:

the gamma dose rate (or shield thickness), the half- and tenth-value thicknesses of shield material and the specific gamma dose rate constant.

A list of all energy lines and emission probabilities used in the calculation are given.

Subsidiary quantities used in the calculations, such as the absorption coefficient, number of mean free path in the shield material, and the build-up factor for each energy line are given.

Finally, the gamma dose rate contribution from each energy line is listed. Finally, a spectrum of the lines used in the calculations can be viewed by using the Graph button.

| | |
|---|---|
| Half-Value Shield Thickness(cm) | 2.02E+00 |
| Tenth-Value Shield Thickness(cm) | 5.03E+00 |
| Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h) | 3.37E-01 |
| **Gamma Dose Rate (µSv/h)** | **2.67E-01** |
| Effective Build-up factor | 1.55E+00 |
| Effective Number of Mean Free Paths (µ·d) | 6.70E-01 |

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| | | | |
|---|---|---|---|
| Number of lines (γ): | 6 | ΣE.P.(γ): | 2.50E+06 |
| Number of lines (X): | 4 | ΣE.P.(X): | 8.35E-01 |
| Number of lines (γ+X): | 10 | ΣE.P.(total): | 2.50E+06 |

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| Gamma Energy (keV) | Emission Probability P (per disintegration) | Mass Attenuation Coefficient (shielding)(cm²/g) | Number of Mean Free Paths (µ·d) | Build-up Factor | Mass Absorption Coefficient (tissue)(cm²/g) | Gamma Dose Rate(µSv/h) |
|---|---|---|---|---|---|---|
| 1.33E+03 | 1.00E+00 | 5.64E-02 | 6.40E-01 | 1.53E+00 | 2.89E-02 | 1.43E-01 |
| 1.17E+03 | 9.99E-01 | 6.20E-02 | 7.04E-01 | 1.57E+00 | 2.98E-02 | 1.25E-01 |
| 8.26E+02 | 7.60E-05 | 8.59E-02 | 9.75E-01 | 1.69E+00 | 3.16E-02 | 5.83E-06 |
| 3.47E+02 | 7.50E-05 | 3.05E-01 | 3.46E+00 | 1.80E+00 | 3.21E-02 | 2.18E-07 |
| 7.48E+00 | 6.44E-05 | 2.71E+02 | 3.07E+03 | 1 | 1.22E+01 | 0 |
| 7.46E+00 | 3.27E-05 | 2.72E+02 | 3.09E+03 | 1 | 1.23E+01 | 0 |
| 8.26E+00 | 1.31E-05 | 2.11E+02 | 2.40E+03 | 1 | 9.01E+00 | 0 |
| 2.16E+03 | 1.20E-05 | 4.54E-02 | 5.15E-01 | 1.49E+00 | 2.52E-02 | 2.66E-06 |
| 8.50E-01 | 1.49E-06 | 7.16E+03 | 8.12E+04 | 1 | 5.38E+03 | 0 |
| 2.51E+03 | 2.00E-08 | 4.39E-02 | 4.99E-01 | 1.48E+00 | 2.40E-02 | 4.97E-09 |

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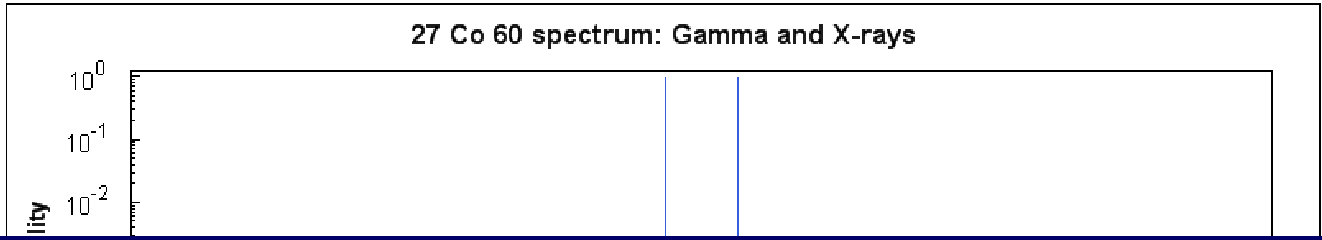

Results:
Finally, a spectrum of the lines used in the calculations can be seen:

| | | | |
|---|---|---|---|
| Number of lines (γ): | 6 | ΣE.P.(γ): | 2.50E+06 |
| Number of lines (X): | 4 | ΣE.P.(X): | 8.35E-01 |
| Number of lines (γ+X): | 10 | ΣE.P.(total): | 2.50E+06 |

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| Gamma Energy (keV) | Emission Probability P (per disintegration) | Mass Attenuation Coefficient (shielding)(cm²/g) | Number of Mean Free Paths (μ·d) | Build-up Factor | Mass Absorption Coefficient (tissue)(cm²/g) | Gamma Dose Rate(μSv/h) |
|---|---|---|---|---|---|---|
| 1.33E+03 | 1.00E+00 | 5.64E-02 | 6.40E-01 | 1.53E+00 | 2.89E-02 | 1.43E-01 |
| 1.17E+03 | 9.99E-01 | 6.20E-02 | 7.04E-01 | 1.57E+00 | 2.98E-02 | 1.25E-01 |
| 8.26E+02 | 7.60E-05 | 8.59E-02 | 9.75E-01 | 1.69E+00 | 3.16E-02 | 5.83E-06 |
| 3.47E+02 | 7.50E-05 | 3.05E-01 | 3.46E+00 | 1.80E+00 | 3.21E-02 | 2.18E-07 |
| 7.48E+00 | 6.44E-05 | 2.71E+02 | 3.07E+03 | 1 | 1.22E+01 | 0 |
| 7.46E+00 | 3.27E-05 | 2.72E+02 | 3.09E+03 | 1 | 1.23E+01 | 0 |
| 8.26E+00 | 1.31E-05 | 2.11E+02 | 2.40E+03 | 1 | 9.01E+00 | 0 |
| 2.16E+03 | 1.20E-05 | 4.54E-02 | 5.15E-01 | 1.49E+00 | 2.52E-02 | 2.66E-06 |
| 8.50E-01 | 1.49E-06 | 7.16E+03 | 8.12E+04 | 1 | 5.38E+03 | 0 |
| 2.51E+03 | 2.00E-08 | 4.39E-02 | 4.99E-01 | 1.48E+00 | 2.40E-02 | 4.97E-09 |

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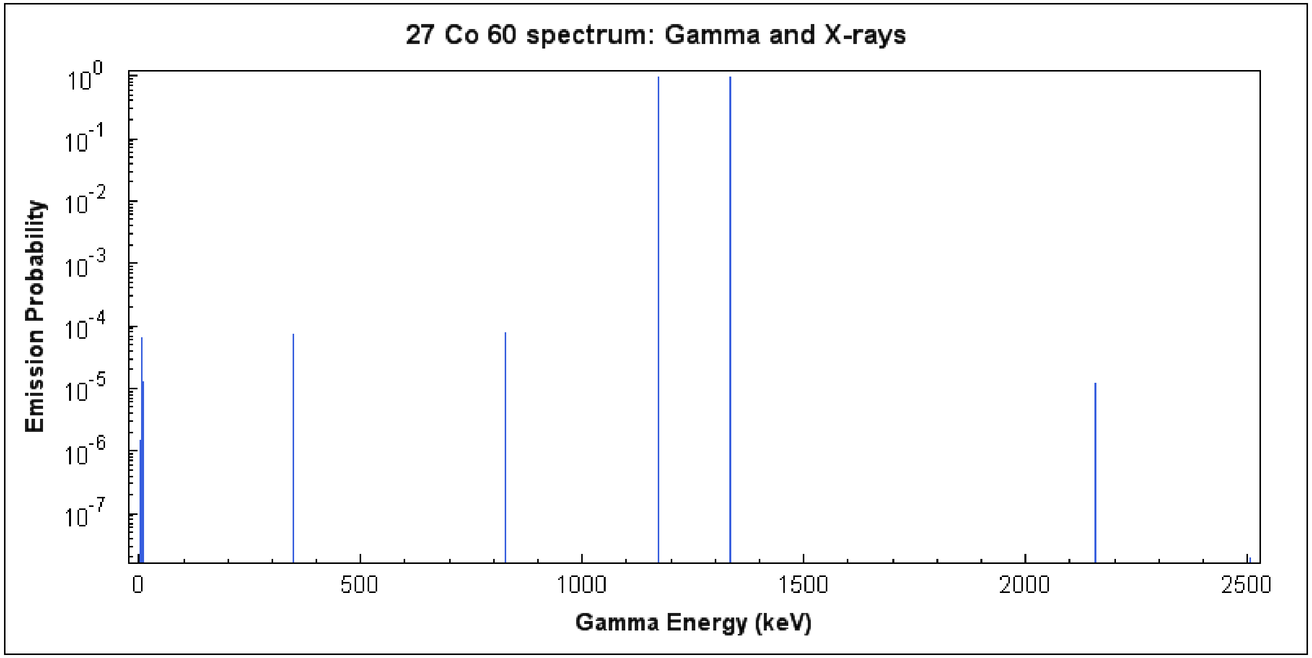
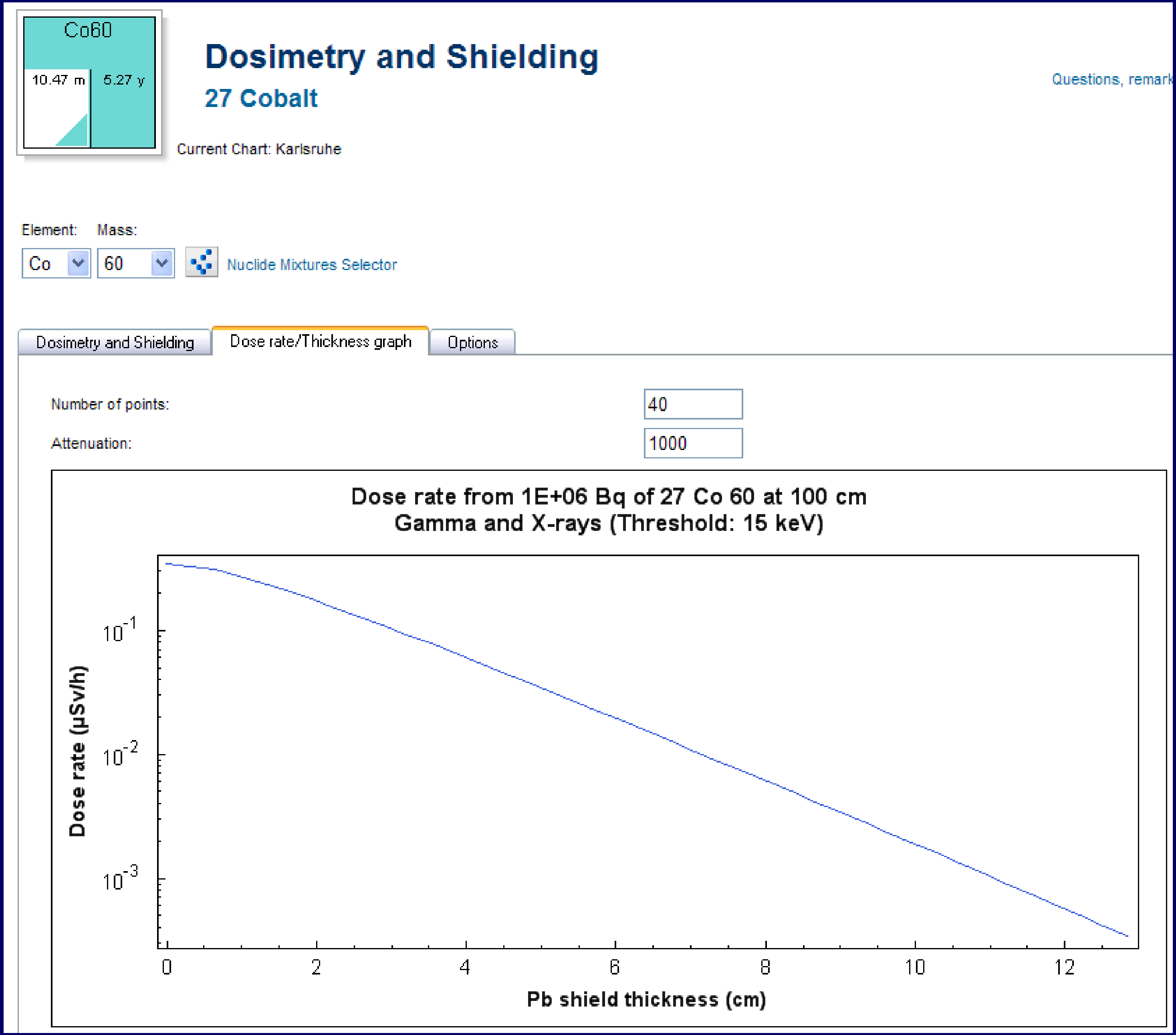
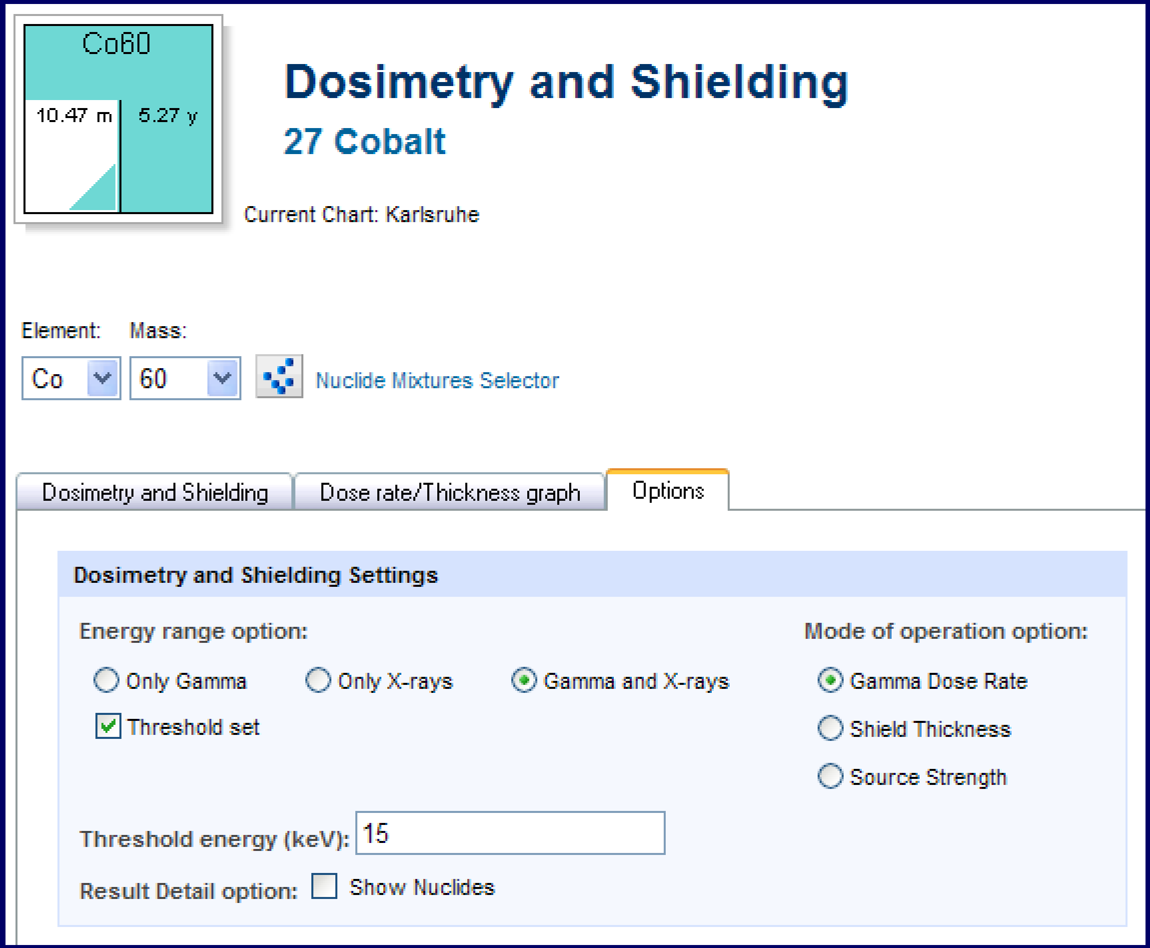


# Dose Rate / Thickness Tab

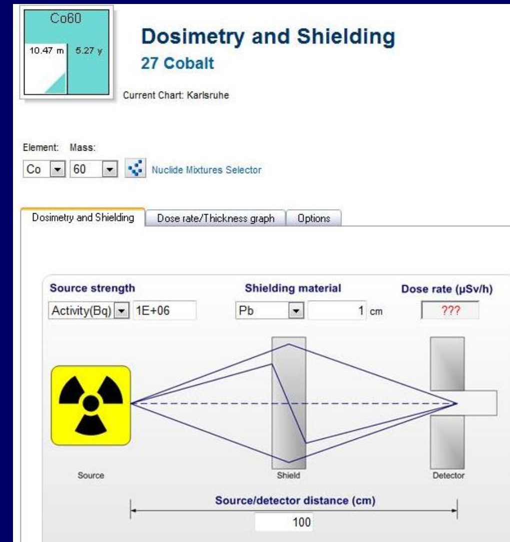


Options Tab:

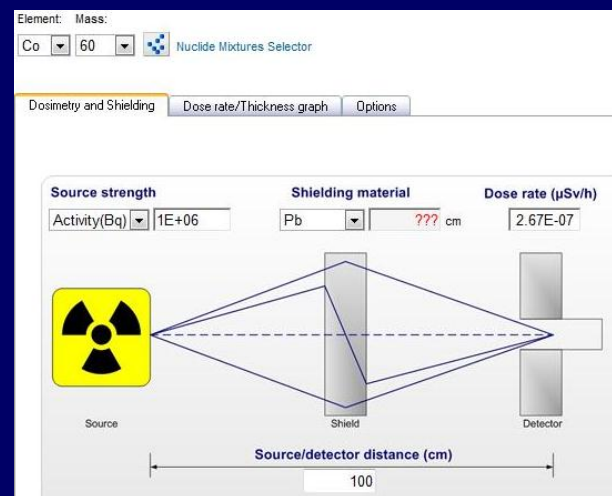
In the Energy range option, the user can choose to include only gammas, X-rays, or both in the calculation. In addition the user can set the minimum (threshold) energy of gamma and X-rays to be included in the calculation. The default value is 15 keV – photons with lower energy are absorbed by the outer layers of human tissue.



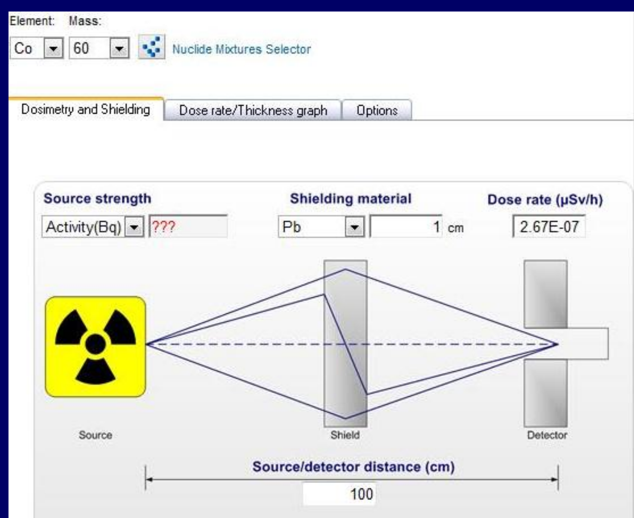
• Calculation of the dose rate for a given shield material and thickness.




• Calculation of the thickness of shield material required to obtain a given dose rate




• Obtain the source strength when the dose rate, shield material and thickness are known



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## Biological Effects of Ionising Radiation

- Absorber dose, Quality or Weighting Factor, Equivalent Dose

## Attenuation of Gamma Radiation

- Calculation of the energy absorption, calculation of the equivalent dose rate, absorption in tissue, attenuation in shield materials, build-up factors

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